ISSN 2712-8008
Volume / Том 23 №1 2023
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622+624.131.1
Article / Статья

On the Question of Engineering and Geological Zoning of Territories within Local Tectonic Structures

Sharibzan Kh. Gainanov

Perm State National Research University (15 Bukireva st., Perm, 614068, Russian Federation)

К вопросу инженерно-геологического районирования территорий в пределах локальных тектонических структур

Ш.Х. Гайнанов

Пермский государственный национальный исследовательский университет (Россия, 614068, г. Пермь, ул. Букирева, 15)

Received / Получена: 15.09.2022. Accepted / Принята: 19.12.2022. Published / Опубликована: 31.05.2023

Keywords:
local tectonic structures, tectonic fracturing, stresses, deformations, rock structure, rock properties, criteria for identifying weakened zones of a massif, hypergenesis, exogenous processes.

The relevance of the research lies in the approach to assessing the engineering-geological conditions within the local tectonic structures and their role in the formation of the properties of rocks and the state of the massifs composed by them. The formulation of the question regarding the rocks of the red-colored terrigenous formation as a separate object of engineering and geological research allows us to take into account the features of the history and mechanism of development of local structures, as well as their influence on the reaction of rocks in this case. Particular attention is paid to the role of tectonic fracturing as a consequence of the mechanism of development of local structures and its influence on the activation of hypergenesis processes.
An analysis of the behavior of rocks during the development of local structures and the response of the massif to changes in the state of rocks and the activation of hypergenesis processes was carried out, which, in turn, determined the engineering-geological situation at the current moment. Particular attention was paid to the assessment of tectonic fracturing, identification of weakened zones and criteria confirming the correctness of their identification. The methods used in solving the tasks were reduced to a comprehensive study of local structures: the study of the history of their development, size, amplitude of uplift of the foundation, instrumental survey of fracturing in outcrops with subsequent construction of a map of fracturing, sampling, laboratory studies of the structure and properties of rocks, fixation of exogenous processes within the structure.
The results of the research were the established dependences of the influence of tectonic fracturing on the state of rocks at three levels: the microlevel (the reaction of the minerals of the constituent rocks at the level of the crystal lattice in the form of defects that have arisen); mesolevel (changes in the physical and mechanical properties of rocks); macrolevel (activation of exogenous processes). Thus, criteria have been defined that allow using them to confirm the correctness of the selection of the most fractured sections of the massif. The correctness of the methodology for identifying zones of increased fracturing within local structures is confirmed by the criteria that were used to solve this problem. It can be used as a basis for large-scale geotechnical zoning within local tectonic structures.

Ключевые слова:
локальные тектонические структуры, тектоническая трещиноватость, напряжения, деформации, строение пород, свойства пород, критерии при выделении ослабленных зон массива, гипергенез, экзогенные процессы.

Актуальность исследований заключается в подходе к оценке инженерно-геологических условий в пределах локальных тектонических структур и их роли в формировании свойств пород и состояния массивов, ими сложенных. Постановка вопроса относительно пород красноцветной терригенной формации как отдельного объекта инженерно-геологических исследований позволяет учитывать особенности истории и механизма развития локальных структур, а также их влияние на реакцию пород при этом. Особое внимание уделяется роли тектонической трещиноватости, как следствию механизма развития локальных структур и ее влиянию на активизацию процессов гипергенеза.
Осуществлен анализ поведения пород в ходе развития локальных структур и реакции массива на изменение состояния пород и активизацию процессов гипергенеза, что, в свою очередь, определяет инженерно-геологическую ситуацию на текущий момент. Особое внимание уделяется оценке тектонической трещиноватости, выделению ослабленных зон и критериям, подтверждающих корректность их выделения.
Методы, применяемые при решении поставленных задач, сводились к комплексному изучению локальных структур: изучение истории их развития, размеров, амплитуды поднятия фундамента, инструментальная съемка трещиноватости в обнажениях с последующим построением карты трещиноватости, отбор образцов, лабораторные исследования строения и свойств пород, фиксация экзогенных процессов в пределах структуры.
Результатом исследований явились установленные зависимости влияния тектонической трещиноватости на состояние пород на трех уровнях: микроуровень (реакция минералов слагающих пород на уровне кристаллической решетки в виде возникших дефектов); мезоуровень (изменения физико-механических свойств пород); макроуровень (активизация экзогенных процессов). Таким образом, определены критерии, которые позволяют использовать их для подтверждения корректности выделения наиболее нарушенных трещиноватостью участков массива. Корректность методики выделения зон повышенной трещиноватости в пределах локальных структур подтверждена критериями, которые были использованы для решения этой задачи. Она может быть использована в качестве основы при крупномасштабном инженерно-геологическом районировании в пределах локальных тектонических структур.

© **Sharibzan Kh. Gainanov** – Associate Professor, Associate Professor of the Department of Engineering Geology and Subsoil Protection, PhD in Geological and Mineralogical Sciences (tel.: +007 902 472 75 41, e-mail: gaynanov@inbox.ru).

© **Гайнанов Шарибзан Хатинович** – доцент, доцент кафедры инженерной геологии и охраны недр, кандидат геолого-минералогических наук (тел.: +007 (902) 472 75 41, e-mail: gaynanov@inbox.ru).

Please cite this article in English as:
Gainanov S.Kh. On the question of engineering and geological zoning of territories within local tectonic structures. *Perm Journal of Petroleum and Mining Engineering*, 2023, vol.23, no.1, pp.18-24. DOI: 10.15593/2712-8008/2023.1.3

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Гайнанов Ш.Х. К вопросу инженерно-геологического районирования территорий в пределах локальных тектонических структур // Недропользование. – 2023. – Т.23, №1. – С.18–24. DOI: 10.15593/2712-8008/2023.1.3

Introduction

The necessity to address the issue of geotechnical zoning of territories within local tectonic structures is caused by a number of reasons. The author's earlier research of the features of the conditions for the formation of geotechnical properties of rocks of the terrigenous red formation indicate a significant role of local structures in the course of their development and influence on the rocks and massifs state. Change in physical and mechanical properties of rocks are closely related to the history of local tectonic structures development by the mechanism of their formation which led to the creation of prerequisites for the activation of hypergenesis processes and, as a result, to the transformation of the quality of rocks and the state of the masses composed by them.

Local structures of the third order are widely developed on the territory of the distribution of the red-colored terrigenous formation of the eastern part of the Russian platform. The mechanism and conditions of their formation have been studied by a number of researchers (L.N. Rozanov, V.V. Belousov, Yu.A. Kosygin, E.W. Spencer, A.P. Vinogradov, A.B. Ronov) [1–8] and others. They found that the peculiarities of the formation of structures on the platforms are determined by the nature of the prevailing tectonic movements, their vertical orientation. Block tectonics of the platform basement is the main factor in the formation of sedimentary cover structures. Among the studies devoted to this problem it should be noted the works of L.N. Rozanov [2] with a detailed analysis of the mechanism of structures formation and their varieties. An important consequence of this is the occurrence of tectonic fracturing which served as an impetus and catalyst for the activation of hypergenesis processes. The impact of fracturing on the condition of rocks and massifs was generally assessed by many researchers from a practical point of view [9, 10]. Great importance is attached to the assessment of rock fracturing in the design of hydraulic structures [11–13], as well as its role in explaining the reasons for a wide range of rock strength characteristics in a limited area of the massif [14–17]. A significant amount of work has recently been devoted to solving local problems, such as assessing the sides of quarries, when it is determined a connection between fracturing and violation of the strength characteristics of rocks affecting the stability of individual blocks of the massif. It is also assessed water abundance in certain areas of fields which is associated with increased fracturing [18–23]. To solve these problems, mathematical modeling methods are widely used. At that, both the state of the massif as a whole [24–28], and the reaction of rock-forming minerals and defects arising in them under the influence of high stresses in rock masses [29–39] are assessed.

Methodological Approach to the Territories Typing within Local Structures

From the point of view of engineering geology it is the matter of topical interest the problem of identifying the weakened zones within the entire area of the massif and the mechanism of propagation of areas with the

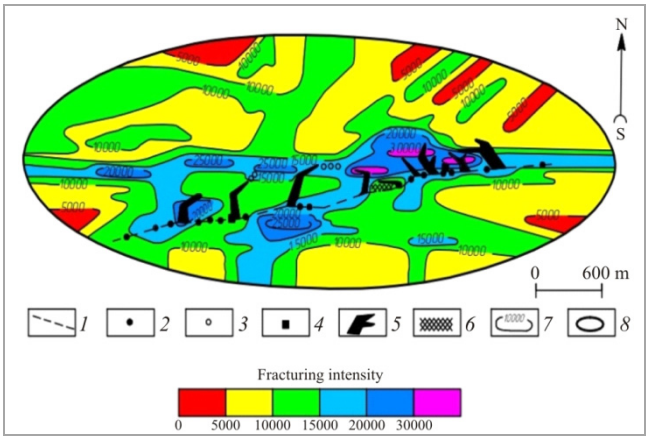

Fig. 1. Schematic map of fracturing distribution within Opalikhinskaya local structure: *1* – outcrop line; *2* – sampling points; *3* – suffosion subsidences; *4* – clearing locations; *5* – ravines; *6* – area of outcrop within which landslide is developed; *7* – isolines of fracturing intensity index; *8* – boundary of the structure

increased fracturing in order to establish the least favorable areas for their development. At one time, E.N. Permyakov [40] and M.V. Gzovsky [41–43] tried to define the nature of crack development within local structures using physical modeling. The data presented in these works confirmed the general principles of fracturing development in massifs. However, they could not take into account a number of factors in each individual structure related to the history of its formation (geometric characteristics, axis dimensions, amplitude of the foundation block rise, deformation properties of rocks, etc.). The proposed methodology involves a first-stage study of the geological characteristics of a particular structure and its parameters, followed by consducting an instrumental survey in the field in order to construct a fracturing map.

In carrying out field work and constructing fracturing maps it was the technique applied earlier by N.V. Kataev [44] and A.I. Pecherkin [45] at the Department of Engineering Geology and Subsoil Protection of Perm State National Research University (PSNRU) to solve kastorological problems and published in [46]. The author applied this methodology in assessing the fracturing of a number of local structures on the coast of the Kama reservoirs (Opalikhinskaya, Romanikha, Izhevsk source structures). During the fracturing survey rock samples were taken from outcrops and were studied in laboratory conditions. A fracturing map was constructed on the base of the fracturing survey results (Fig. 1).

The principles proposed for solving this problem are based on the methods of fracturing maps generation for local structures, where, according to the results of a comprehensive study of the massif, the correctness of the selection of these zones is confirmed at different levels of the state of rocks:

– micro level – reaction of the crystal lattice to the development and occurrence of fracturing;

– meso level – change in the physical and mechanical properties of rocks in fractured areas of the structure;

– macro level – activation of exogeneous processes in zones of increased tectonic fracturing Thus, the proposed methodology involves two main stages:

Stage 1 – construction of fracturing map of the local structure;

Stage 2 – study of the rocks condition in order to assess the correctness of fracturing zone identification.

Changes in the rocks condition at the micro level are essentially the basis for the beginning of the activation of hypergenesis processes and they are associated with violations of the structure of the crystal lattice during the occurrence of stresses in the rocks and, as a result, deformations with the subsequent formation of fracturing. At natural occurrence, rocks, being in thermodynamic equilibrium with the environment, can record a change in the geological situation in the crystal structure of their constituent minerals, variations in composition and texture. Interpretation of the information encoded in the lattice of minerals, the composition and structural and textural features of rocks allows us to obtain data for the reconstruction of the nature and mechanism of processes and the formation of rock properties [47, 48]. To obtain answers to these questions, the author used X-ray diffraction analysis. To characterize the microtext, a texture index (≤ ½) was used, measured in degrees, as well as an indicator of the instrumental width of the scattering intensity peak (B, mm), which characterizes the crystallite microdeformations. Based on the fact that stresses determining the occurrence of deformations and fracturing should also affect the microtexture of rock-forming minerals, a comparative analysis of the results of X-ray diffraction analysis of samples from zones of different degrees of fracturing within the local structure was carried out. The reaction of rocks at the level of the crystal lattice and the degree of change in their state depending on the fracturing (LT) are shown in Fig. 2.

Violation of the integrity of the rocks of the massif also affects the main rock-forming minerals.

First of all, their ratio changes: the content of the least resistant to hypergenesis decreases in the rock. Calcite, being one of the cement minerals, reacts most sensitively, and its amount decreases significantly in zones of increased fracturing (Fig. 3). Quartz is the most stable mineral.

The described changes in the structure and composition of rocks in zones of increased fracturing caused a deterioration in their density and strength characteristics. This is confirmed by the results of laboratory tests and is shown in Figures 4 and 5.

Thus, the change in the physical and mechanical properties of rocks in zones of increased tectonic fracturing is another criterion (at the meso level) to confirm the correctness of the identification of weakened zones within local structures.

The criterion for the influence of tectonic fracturing on the state of the massif at the mesolevel is the activation of exogeneous processes in weakened zones within local structures.

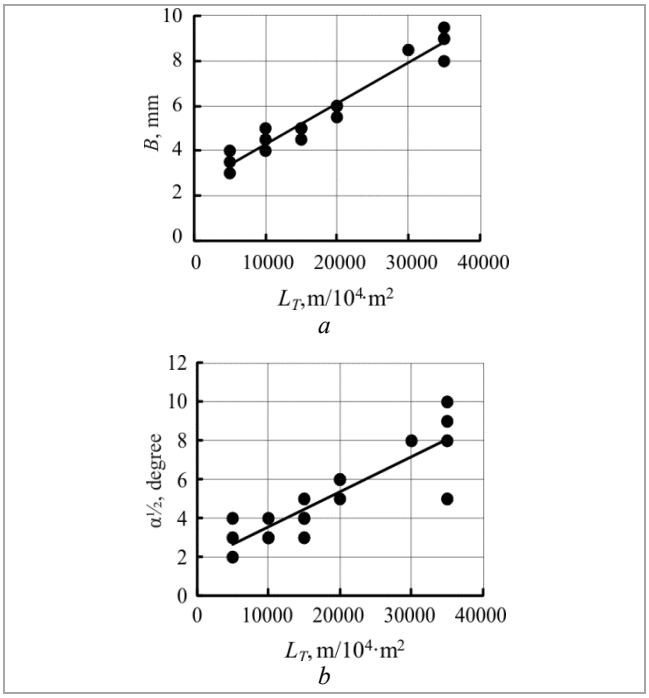

Fig. 2. Relationship between the degree of quartz crystal lattice disturbance of quartz (*B, mm*) and fracturing (LT) (*a*) and the relationship between the degree of quartz crystal lattice disturbance (α ½, °) and fracturing (LT) (*b*)

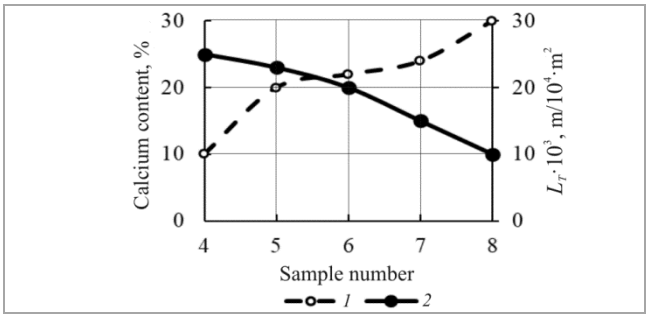

Fig. 3. Effect of tectonic fracturing on calcite content in argillite cement: *1* – calcite content (%); *2* – fracture index (L_T)

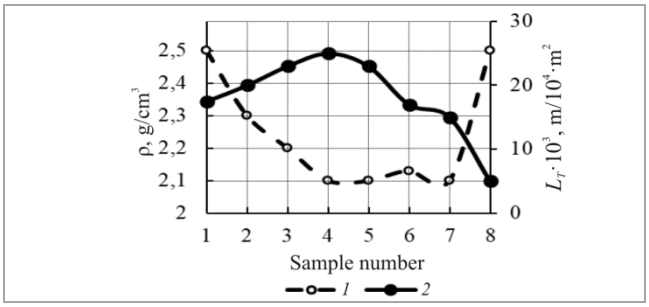

Fig. 4. Influence of tectonica fracturing of the Opalikhinskaya local structure on the density of mudstones: *1* – rock density; *2* – fracture index (L_T)

The author carried out a comparative analysis of the activity of a number of exogeneous processes in the areas of varying degrees of fracturing. So, within the Opalikhinskaya local structure areas of gulley erosion have been mapped (Fig. 6).

The location of the gulleys is observed in the areas with the increased fracturing rates (L_T > 15 000 m/10ha). In addition, fracturing controls the length and direction

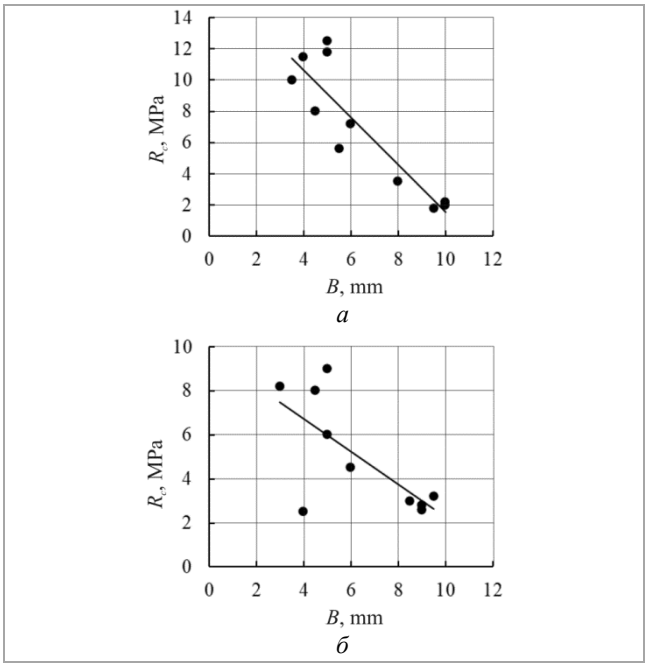

Fig. 5. Influence of quartz crystal lattice disturbance (V, mm) on the strength (R_c, MPa) of sandstones (*a*) and mudstones (*b*)

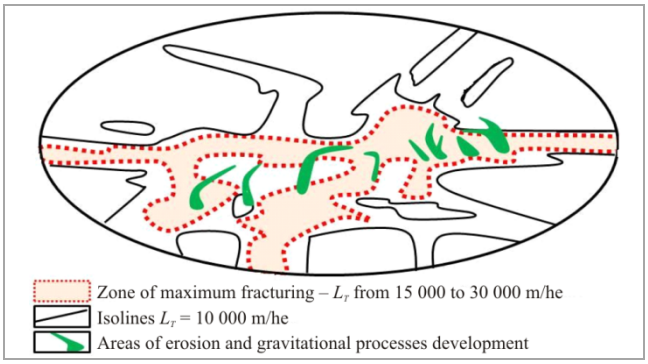

Fig. 6. Spatial correlation diagram of the zone of maximum rock fracturing and areas of development of gully erosion and landslide processes within Opalikhinsky local structure

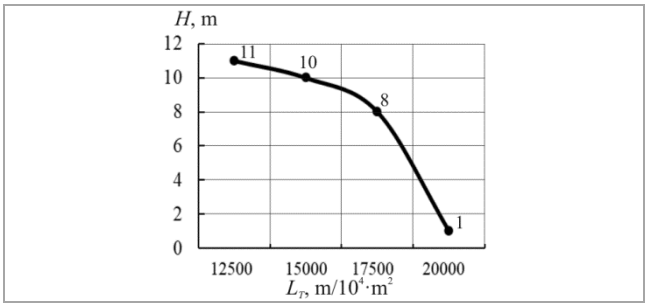

Fig. 7. Effect of local structure fracturing on the height of the abrasion bench of the gulleys thalwegs

of gully erosion. In particular, the growth of gulleys towards the watershed is limited by the zone of maximum fracturing in the axial part of the structure. The central part of the massif (the most fragmented) is also marked by a transition of gullies into the row of suffosion funnels extended along the central axis of the structure.

Another indicator of gully erosion may be the height of the abrasion bench of the gulleys

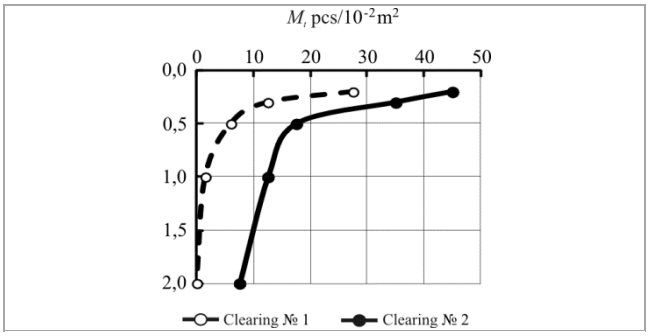

Fig. 8. Change in fracturing modulus of mudstone-like clays with depth

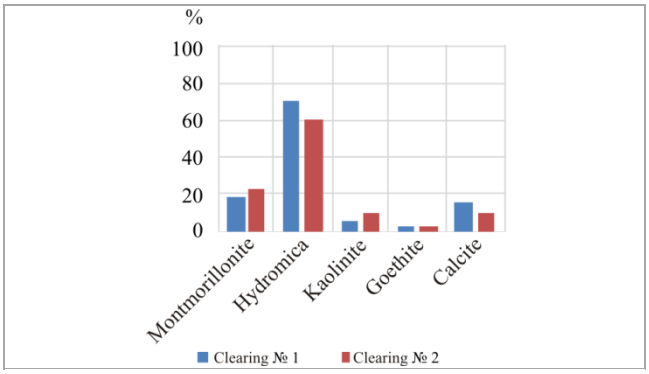

Fig. 9. Mineral content in clearings according to thermal analysis data

thalwegs. The most fragmented areas of the massif are characterized by the minimum height of thalweg (Fig. 7).

Weathering, which is a combination of a number of physical and chemical processes, reacts to the presence of tectonic fracturing especially sensitively, since the disturbed state of the massif rocks creates favorable conditions for the activation of hypergenesis. Since the beginning of the formation of local structures in conditions of high stresses and deformations, there has been a significant restructuring of the of minerals geology aspects, their composition and quantitative ratio. To assess the impact of fracturing on weathering processes clearings were laid in areas with different degrees of fracturing in which the fracturing modulus (Mt) was measured at different depths. Clearing No. 1 – area with reduced fracturing modulus. Clearing area No. 2 in the zone of increased fracturing.

Fig. 8 shows the change in the fracturing modulus of mudstone-like clays in clearings № 1, 2. Fig. 9 shows the mineralogical composition according the thermal analysis data.

Abrasion, the activity of which has been studied on the banks of the Kama reservoirs for more than 30 years by the laboratory of ENI PSNRU, also naturally reacts to the influence of tectonic fracturing. In this case, the rate of processing of banks composed of terrigenous rocks (sandstones and mudstones) located within and outside local structures along reference points was compared. Results of observations are given in Table.

As expected, the rate of bank reformation within local structures due to the presence of fracturing in them exceeds the rate of shore retreat in areas located beyond their boundaries.

Comparison of the intensity of banks reformation within local structures and outside them

Water Storage Reservoir	Reservoir Sector	Average annual values of banks reformation, m/10 years		
		1960–1970 years	1970–1980 years	1980–1990 years
Within the limits of local structures				
Votkinsk	Tolstik	0,5–1,0	0,2–1,2	0,7–1,3
	Novoilyinsk	0,3–0,9	0,6–0,8	0,4–0,9
	Tabory	0,5–1,2	0,6–0,9	0,9–1,2
	Monastyrka	1,5–2,4	1,0–1,8	2,0–3,3
Kama	Kononovka	0,7–1,4	1,2–1,5	0,8–1,2
	Bystraya	0,9–1,5	0,7–1,3	1,3–1,5
	Ust-Garevaya	1,2–1,7	0,9–1,5	1,4–1,0
Average		1,9	1,0	1,3
Outside local structures				
Votkinsk	Dvorcovaya Sludka	0,1–0,3	0,2–0,4	0,0–0,2
	Trikhinyata Kostovatik	0,3–0,5 0,7–0,12	0,3–0,7 0,5–0,7	0,3–0,5 0,3–0,9
Kama	Taman	0,0–0,2	0,1–0,4	0,1–0,3
	Kondas	0,2–0,4	0,1–0,3	0,2–0,3
	Gorodische	0,0–03	0,4–0,8	0,3–1,0
	Ust-Kosva	0,2–0,3	0,3–0,5	0,0–0,3
Average		0,3	0,4	0,4

Conclusion

The technique for identifying zones of increased fracturing within local tectonic structures can be used in engineering and geological assessment of the territory of massifs in order to predict the most unfavorable areas for engineering development and those requiring special attention in the process of performing design work and special design solutions.

The correctness of indentifying zones of increased fracturing is confirmed by a set of criteria at different levels:microlevele – state of the crystal lattice; meso level – physical and mechanical propeties of rocks; macro level – activation of exogeneous processes.

The close correlation of these criteria with the intensity of tectonic fracturing (LT) allows using this indicator as a base for determining zones of varying degrees of disturbance in the massif.

Identification of taxa by indicator (LT) within local structires can be used to solve problems in large-scale engineering-geological zoning.

References

1. Rozanov L.N. Osnovnye zakonomernosti morfologii i prichiny obrazovaniia tektonicheskikh struktur [The main regularities of morphology and the reasons for the formation of tectonic structures]. Leningrad: Gostoptekhizdat, 1962, 84 p.
2. Rozanov L.N. Dinamika formirovaniia tektonicheskikh struktur platformennykh oblastei [Dynamics of formation of tectonic structures of platform areas]. Leningrad: Nedra, 1981, 140 p.
3. Belousov V.V. Tektonicheskie razryvy, ikh tipy i mekhanizm obrazovaniia [Tectonic faults, their types and mechanism of formation]. Moscow: Akademiia nauk SSSR, 1952, 147 p.
4. Belousov V.V. Geotektonika [Geotectonics]. Moscow: Moskovskii gosudarstvennyi universitet, 1976, 334 p.
5. Kosygin Iu.A. Tektonika [Tectonics]. Moscow: Nedra, 1983, 536 p.
6. Spenser E.U. Vvedenie v strukturnuiu geologiiu [Introduction to structural geology]. Leningrad: Nedra, 1981, 367 p.
7. Vinogradov A.P., Ronov A.B. Sostav osadochnykh porod Russkoi platformy v sviazi s istoriei ee tektonicheskikh dvizhenii [The composition of sedimentary rocks of the Russian platform in connection with the history of its tectonic movements]. *Geokhimiia*, 1956, no. 6, pp. 3-24.
8. Ronov A.B., Girin Iu.P., Kazakov G.A., Iliukhin M.N. Sravnitel'naia geokhimiia geosinklinal'nykh i platformennykh osadochnykh tolshch [Comparative geochemistry of geosynclinal and platform sedimentary strata]. *Geokhimiia*, 1965, no. 8, pp. 961-976.
9. Rats M.V. Strukturnye modeli v inzhenernoi geologii [Structural models in engineering geology]. Moscow: Nedra, 1973, 216 p.
10. Chernyshev S.N. Treshchiny gornykh porod [Rock cracks]. Moscow: Nedra, 1983, 240 p.
11. Reuter F., Klengel J., Pasek J. Ingenieurgeologie. Leipzig: VEB Deutscher Verlag für Grundstoffindustrie, 1980, 451 p.
12. Dittrich E. Beobachtungen uber den Kluftkorper. *Bergakademie*, 1970, 3, pp. 151-160.
13. Georgi F., K.H. Hoffer O. u.a. Untersuchungen zum Bruch- und Vormungverhalten des Gebirgsverhaltens. *Neue Bergbautechnik*, 1971, 9, pp. 692-690.
14. Muller L. Der Felsbau. 1 Bd. Wien: Springer Verlag, 1963, 200 p.
15. Gainanov Sh., Reuter F., Ulrich B., Kataev W. Beitrag zur ingenieurgeologischen Beschreibung von permischen Rotsedimenten. *Neue Bergbautechnik*, 1989, vol. 7, pp. 241-245.
16. Gainanov Sh.Kh. Vliianie tektonicheskikh napriazhenii v massivakh porod na izmenenie ikh stroeniia i svoistv [Tectonic stresses impact on rock mass structure and properties]. *Izvestiia vysshikh uchebnykh zavedenii. Gornyi zhurnal*, 2021, no. 3, pp. 71-78. DOI: 10.21440/0536-1028-2021-3-71-78
17. Gainanov Sh., Reuter F. Der Einfluss der tektonischen Beanspruchung von Gestein und Gebirge auf die Entwicklung ihrer physikalisch-mechanischen Eigenschaften - ausgewahlte Beispiele. *Neue Bergbautechnik*, 1983, vol. 12, pp. 681-684.
18. Ikonnikov E.A., Kataev V.N., Ermolovich I.G. Povyshenie effektivnosti vyiavleniia vodoobil'nykh treshchinnykh zon v fatsial'no-nevyderzhannykh peschano-glinistykh tolshchakh [Increasing the efficiency of detecting water-abundant fractured zones in facially unsettled sandy-clay strata]. *Kompleksnye problemy gidrogeologii: materialy nauchnoi konferentsii*. Saint Petersburg: Sankt-Peterburgskii universitet, 2011, pp. 72-74.
19. Tian S.G., Dolgonosov V.N. Izuchenie treshchinovatosti porod na mestorozhdenii “Severnyi Katpar” [Study of cracking of breeds on "Northern Katpar" deposit]. *Molodoi uchenyi*, 2020, no. 20(310), pp. 145-150, available at: https://moluch.ru/archive/310/69958/ (accessed 23 April 2023).

20. Lugantsev B.B. Obespechenie ustoichivosti podzemnykh gornykh vyrabotok v treshchinovatom porodnom massive [Ensuring the stability of underground mine workings in a fractured rock mass]. Abstract of Ph. D. thesis. Moscow, 2001, 36 p.
21. Korchak S.A., Abaturova I.V., Savintsev I.A., Storozhenko L.A. Otsenka sostoianiia massiva gornykh porod dlia vydeleniia potentsial'no opasnykh uchastkov proektiruemogo kar'era [Rock mass quality assessment to reveal potentially hazardous areas in open pit mine design]. *Gornyi informatsionno-analiticheskii biulleten'*, 2022, no. 9, pp. 87-98. DOI: 10.25018/0236_1493_2022_9_0_87
22. Kuz'min V.S., Kopytin A.S. Primenenie komp'iuternykh tekhnologii dlia resheniia zadach, sviazannykh s izucheniem treshchinovatosti skal'nykh massivov [Application of computer technologies for solving problems related to the study of fractures in rock masses]. *Vestnik Rossiiskogo universiteta druzhby narodov. Ekologiia i bezopasnost' zhiznedeiatel'nosti*, 2013, no. 3, pp. 83-92.
23. Kakimi T. Depth of fracturing in Earths crust. *Journal of the Geological Society of Japan*, 1971, vol. 77, no. 5, pp. 237-242.
24. Korchak S.A. Poluchenie iskhodnykh dannykh dlia postroeniia prognoznoi inzhenerno-geologicheskoi modeli [Obtaining initial data for forecast engineering geological model construction]. *Izvestiia vysshikh uchebnykh zavedenii. Gornyi zhurnal*, 2022, no. 5, pp. 66-76. DOI: 10.21440/0536-1028-2022-5-66-76
25. Mingazutdinov A.N., Semenova O.V. Prognozirovanie razvitiia zon treshchinovatosti s pomoshch'iu issledovaniia orientirovannogo kerna [Predicting rock-fracture zone development based on oriented core analysis]. *Neftianaia provintsiia*, 2017, no. 3(11), pp. 84-95. DOI: 10.25689/NP.2017.3.84-95
26. Seredin V.V., Khrulev A.S., Rastegaev A.V., Galkin V.I. Metodika otsenki napriazhennogo sostoianiia gornykh porod [Procedure of stress state assessment in rocks]. *Gornyi zhurnal*, 2020, no. 2, pp. 30-34. DOI: 10.17580/gzh.2020.02.03
27. Siegesmund S., Snethlage R. Stone in architecture: properties, durability. Berlin: Springer, 2011, 558 p.
28. Wang Rui, Deng Xianghui, Meng Yaoyao, Xia Daohong. Application of ultrasonic-rebound method in fast prediction of rock strength. *Geotechnical and Geological Engineering. International Journal*, 2020, vol. 38, pp. 5915-5924. DOI: org/10.1007/s10706-020-01402-6
29. Zhuravkov M.A. Matematicheskoe modelirovanie deformatsionnykh protsessov v tverdykh deformiruemykh sredakh (na primere zadach mekhaniki gornykh porod i massivov) [Mathematical modeling of deformation processes in solid deformable media (on the example of problems of mechanics of rocks and massifs)]. Minsk: Belorusskii gosudarstvennyi universitet, 2002, 456 p.
30. Zakrevskii K.E., Kundin A.S. Osobennosti geologicheskogo 3D modelirovaniia karbonatnykh i treshchinovatykh rezervuarov [Features of geological 3D modeling of carbonate and fractured reservoirs]. Moscow: Belyi veter, 2016, 404 p.
31. Konstantinova S.A., Aptukov V.N. Nekotorye zadachi mekhaniki deformirovaniia i razrusheniia solianykh porod [Some problems in the mechanics of deformation and fracture of salt rocks]. Novosibirsk: Nauka, 2013, 191 p.
32. Livinskii I.S., Mitrofanov A.F., Makarov A.B. Kompleksnoe geomekhanicheskoe modelirovanie: struktura, geologiia, razumnaia dostatochnost' [Complex geomechanical modeling: structure, geology, reasonable sufficiency]. *Gornyi zhurnal*, 2017, no. 8, pp. 51-55. DOI: 10.17580/gzh.2017.08.09
33. Oloviannyi A.G. Matematicheskoe modelirovanie protsessov deformirovaniia i razrusheniia v treshchinovatykh massivakh gornykh porod [Mathematical modeling of deformation processes and failure in fractured rock mass]. *Zapiski gornogo instituta*, 2010, vol. 185, pp. 95-98.
34. Red'kin G.M. Matematicheskoe modelirovanie treshchinovatosti massiva gornykh porod [Mathematical modeling of fractures in a rock mass]. *Izvestiia vuzov. Severo-Kavkazskii region. Tekhnicheskie nauki*, 2005, no. 4, pp. 79-82.
35. Nicholson G.A., Bieniawski Z.T. A nonlinear deformation modulus based on rock mass classification. *International Journal of Mining and Geological Engineering*, 1990, vol.8, pp. 181-202. DOI: org/10.1007/BF01554041
36. Chemenda A.I., Hassani R., Fan J. Numerical modeling of the opening mode fracturing emanating from deformation localization in layered rocks. *Computers and Geotechnics*, 2022, vol. 147. DOI: org/10.1016/j.compgeo.2022.104774
37. Zhou Guang-lei, Xu Tao, Heap Michael J., Meredith Philip G., Mitchell Thomas M., Ashley Stanton-Yonge Sesnic, Yuan Yang. A three-dimensional numerical meso-approach to modeling time-independent deformation and fracturing of brittle rocks. *Computers and Geotechnics*, 2020, vol. 117. DOI: org/10.1016/j.compgeo.2019.103274
38. Wang Chengwen, Liu Xiaoli, Song Danqing, Wang Enzhi, Zhang Jianmin. Elasto-plastic analysis of the surrounding rock mass in circular tunnel using a new numerical model based on generalized nonlinear unified strength theory. *Computers and Geotechnics*, 2023, vol. 154. DOI: org/10.1016/j.compgeo.2022.105163
39. Vlad S.V. O chislennom modelirovanii treshchinovatykh skal'nykh massivov pri geotektonicheskikh nagruzkakh [On numerical modeling of fractured rock massifs under geotectonic loads]. *Promyshlennoe i grazhdanskoe stroitel'stvo*, 2014, no. 11, pp. 32-35.
40. Permiakov F.N. Tektonicheskaia treshchinovatost' Russkoi platformy [Tectonic jointing of the Russian platform]. Moscow: Moskovskoe obshchestvo ispytatelei prirody, 1949, 215 p.
41. Gzovskii M.V. Tektonofizicheskie predstavleniia o napriazhennom sostoianii zemnoi kory [Tectonophysical ideas about the stress state of the earth's crust]. *Sovremennye problemy mekhaniki gornykh porod. Materialy 4-i Vsesoiuznoi konferentsii po mekhanike gornykh porod*. Leningrad: Nauka, 1972, pp. 125-146.
42. Gzovskii M.V. Osnovy tektonofiziki [Fundamentals of tectonophysics]. Moscow: Nauka, 1975, 536 p.
43. Belousov V.V., Gzovskii M.V. Eksperimental'naia tektonika [Experimental tectonics]. Moscow: Nedra, 1964, 119 p.
44. Kataev V.N., Pecherkin A.I., Pecherkin I.A. Modelirovanie polei napriazhenii pri obrazovanii i razvitii lokal'nykh struktur platformennogo tipa [Modeling of stress fields during the formation and development of platform-type local structures]. *Modelirovanie v gidrogeologii i inzhenernoi geologii*, 1983, pp. 89-93.
45. Pecherkin A.I. K raschetu napriazhenii, voznikaiushchikh pri formirovanii struktur polnoi skladchatosti [On the calculation of stresses arising during the formation of structures of complete folding]. *Inzhenernaia geologiia*, 1987, no. 2, pp. 95-105.
46. Gainanov Sh.Kh., Kataev V.V. Vyiavlenie zon treshchinovatosti v predelakh lokal'nykh struktur, slozhennykh terrigennymi krasnotsvetnymi porodami [Identification of fracture zones within local structures composed of terrigenous red-colored rocks]. *Inzhenernaia geologiia*, 1988, no. 6, pp. 92-97.
47. Ponomarev V.V. Rentgenostrukturnye metody issledovaniia v inzhenernoi geologii [X-ray structural research methods in engineering geology]. Moscow: Nedra, 1981, 194 p.
48. Rusakov A.A. Rentgenografiia metallov [Radiography of metals]. Moscow: Atomizdat, 1977, 480 p.

Библиографический список

1. Розанов Л.Н. Основные закономерности морфологии и причины образования тектонических структур. – Л.: Гостоптехиздат, 1962. – 84 с.
2. Розанов Л.Н. Динамика формирования тектонических структур платформенных областей. – Л.: Недра, 1981. – 140 с.
3. Белоусов В.В. Тектонические разрывы, их типы и механизм образования. – М.: АН СССР, 1952. – 147 с.
4. Белоусов В.В. Геотектоника. – М.: Изд-во МГУ, 1976. – 334 с.
5. Косыгин Ю.А. Тектоника. – М.: Недра, 1983. – 536 с.
6. Спенсер Э.У. Введение в структурную геологию. – Л.: Недра, 1981. – 367 с.
7. Виноградов А.П., Ронов А.Б. Состав осадочных пород Русской платформы в связи с историей ее тектонических движений // Геохимия. – 1956. – №6. – С.3–24.
8. Сравнительная геохимия геосинклинальных и платформенных осадочных толщ / А.Б. Ронов, Ю.П. Гирин, Г.А. Казаков, М.Н. Илюхин // Геохимия. – 1965. – №8. – С. 961–976.
9. Рац М.В. Структурные модели в инженерной геологии. – М.: Недра, 1973. – 216 с.
10. Чернышев С.Н. Трещины горных пород. – М.: Наука, 1983. – 240 с.
11. Reuter F., Klengel J., Pasek J. Ingenieurgeologie. Leipzig: VEB Deutscher Verlag für Grundstoffindustrie, 1980. – 451 s.
12. Dittrich E. Beobachtungen uber den Kluftkorper // Bergakademie. – 1970. – 3. – S. 151–160.
13. Georgi F., K.H. Hoffer O. u.a. Untersuchungen zum Bruch- und Vormungverhalten des Gebirgsverhaltens // Neue Bergbautechnik. – 1971. – 9. – S. 692–690.
14. Muller L. Der Felsbau. 1 Bd. – Wien: Springer Verlag, 1963 – 200 s.
15. Beitrag zur ingenieurgeologischen Beschreibung von permischen Rotsedimenten / Sh. Gainanov, F. Reuter, B. Ulrich, W. Kataev // Neue Bergbautechnik. – 1989. – Vol. 7. – S. 241–245.
16. Гайнанов Ш.Х. Влияние тектонических напряжений в массивах пород на изменение их строения и свойств // Известия высших учебных заведений. Горный журнал. – 2021. – № 3. – С. 71–78. DOI: 10.21440/0536-1028-2021-3-71-78
17. Gainanov Sh., Reuter F. Der Einfluss der tektonischen Beanspruchung von Gestein und Gebirge auf die Entwicklung ihrer physikalisch-mechanischen Eigenschaften – ausgewahlte Beispiele // Neue Bergbautechnik. – 1983. – Vol. 12. – S. 681–684.
18. Иконников Е.А., Катаев В.Н., Ермолович И.Г. Повышение эффективности выявления водообильных трещинных зон в фациально-невыдержанных песчано-глинистых толщах // Комплексные проблемы гидрогеологии: материалы научной конференции / Санкт-Петербургский ун-т. – СПб., 2011. – С. 72–74.
19. Тян С.Г., Долгоносов В.Н. Изучение трещиноватости пород на месторождении «Северный Катпар» [Электронный ресурс] // Молодой ученый. – 2020. – №20(310). – С. 145–150. – URL: https://moluch.ru/archive/310/69958/ (дата обращения: 23.04.2023).
20. Луганцев Б.Б. Обеспечение устойчивости подземных горных выработок в трещиноватом породном массиве: автореф. дис. … д-ра тех. наук. – М., 2001. – 36 с.

21. Оценка состояния массива горных пород для выделения потенциально опасных участков проектируемого карьера / С.А. Корчак, И.В. Абатурова, И.А. Савинцев, Л.А. Стороженко // Горный информационно-аналитический бюллетень. – 2022. – № 9. – С. 87–98. DOI: 10.25018/0236_1493_2022_9_0_87
22. Кузьмин В.С., Копытин А.С. Применение компьютерных технологий для решения задач, связанных с изучением трещиноватости скальных массивов // Вестник Российского университета дружбы народов. Серия: Экология и безопасность жизнедеятельности. – 2013. – № 3. – С. 83–92.
23. Kakimi T. Depth of fracturing in Earths crust // Journal of the Geological Society of Japan. – 1971. – Vol. 77, № 5. – P. 237–242.
24. Корчак С.А. Получение исходных данных для построения прогнозной инженерно-геологической модели // Известия высших учебных заведений. Горный журнал. – 2022. – № 5. – С. 66–76. DOI: 10.21440/0536-1028-2022-5-66-76
25. Мингазутдинов А.Н., Семенова О.В. Прогнозирование развития зон трещиноватости с помощью исследования ориентированного керна // Нефтяная провинция. – 2017. – № 3(11). – С. 84–95. DOI: 10.25689/NP.2017.3.84-95
26. Методика оценки напряженного состояния горных пород / В.В. Середин, А.С. Хрулев, А.В. Растегаев, В.И. Галкин // Горный журнал. – 2020. – № 2. – С. 30–34. DOI: 10.17580/gzh.2020.02.03
27. Siegesmund S., Snethlage R. Stone in architecture: properties, durability. – Berlin: Springer, 2011. – 558 p.
28. Application of ultrasonic-rebound method in fast prediction of rock strength / Rui Wang, Xianghui Deng, Yaovao Meng, Daohong Xia // Geotechnical and Geological Engineering. International Journal. – 2020. – Vol. 38. – P. 5915–5924. DOI: org/10.1007/s10706-020-01402-6
29. Журавков М.А. Математическое моделирование деформационных процессов в твердых деформируемых средах (на примере задач механики горных пород и массивов). – Минск: БГУ, 2002. – 456 с.
30. Закревский К.Е., Кундин А.С. Особенности геологического 3D моделирования карбонатных и трещиноватых резервуаров. – М.: Белый ветер, 2016. – 404 с.
31. Константинова С.А., Аптуков В.Н. Некоторые задачи механики деформирования и разрушения соляных пород. – Новосибирск: Наука, 2013. – 191 с.
32. Ливинский И.С., Митрофанов А.Ф., Макаров А.Б. Комплексное геомеханическое моделирование: структура, геология, разумная достаточность // Горный журнал. – 2017. – №8. – С. 51–55. DOI: 10.17580/gzh.2017.08.09
33. Оловянный А.Г. Математическое моделирование процессов деформирования и разрушения в трещиноватых массивах горных пород // Записки горного института. – 2010. – Т. 185. – С. 95–98.
34. Редькин Г.М. Математическое моделирование трещиноватости массива горных пород // Известия ВУЗОВ. Северо-Кавказский регион. Технические науки. – 2005. – № 4. – С.79–82.
35. Nicholson G.A., Bieniawski Z.T. A nonlinear deformation modulus based on rock mass classification // International Journal of Mining and Geological Engineering. – 1990. – Vol.8. – P. 181–202. DOI: org/10.1007/BF01554041
36. Chemenda A.I., Hassani R., Fan J. Numerical modeling of the opening mode fracturing emanating from deformation localization in layered rocks // Computers and Geotechnics. – 2022. – Vol. 147. DOI: org/10.1016/j.compgeo.2022.104774
37. A three-dimensional numerical meso-approach to modeling time-independent deformation and fracturing of brittle rocks / Guang-lei Zhou, Tao Xu, Michael J. Heap, Philip G. Meredith, Thomas M. Mitchell, Ashley Stanton-Yonge Sesnic, Yang Yuan // Computers and Geotechnics. – 2020. – Vol. 117. DOI: org/10.1016/j.compgeo.2019.103274
38. Elasto-plastic analysis of the surrounding rock mass in circular tunnel using a new numerical model based on generalized nonlinear unified strength theory / Chengwen Wang, Xiaoli Liu, Danqing Song, Enzhi Wang, Jianmin Zhang // Computers and Geotechnics. – 2023. – Vol. 154. DOI: org/10.1016/j.compgeo.2022.105163
39. Влад С.В. О численном моделировании трещиноватых скальных массивов при геотектонических нагрузках // Промышленное и гражданское строительство. – 2014. – № 11. – С. 32–35.
40. Пермяков Е.Н. Тектоническая трещиноватость Русской платформы. – М.: Изд-во МОИП, 1949. – 215 с.
41. Гзовский М.В. Тектонофизические представления о напряженном состоянии земной коры // Современные проблемы механики горных пород: материалы 4-й Всесоюз. конф. по механике горных пород. – Л.: Наука, 1972. – С. 125–146.
42. Гзовский М.В. Основы тектонофизики. – М.: Наука, 1975. – 536 с.
43. Белоусов В.В., Гзовский М.В. Экспериментальная тектоника. – М.: Недра, 1964. – 119 с.
44. Катаев В.Н., Печеркин А.И., Печеркин И.А. Моделирование полей напряжений при образовании и развитии локальных структур платформенного типа // Моделирование в гидрогеологии и инженерной геологии. – 1983. – С.89–93.
45. Печеркин А.И. К расчету напряжений, возникающих при формировании структур полной складчатости // Инженерная геология. – 1987. – № 2. – С. 95–105.
46. Гайнанов Ш.Х., Катаев В.В. Выявление зон трещиноватости в пределах локальных структур, сложенных терригенными красноцветными породами // Инженерная геология. – 1988. – № 6. – С. 92–97.
47. Пономарев В.В. Рентгеноструктурные методы исследования в инженерной геологии. – М.: Недра, 1981. – 194 с.
48. Русаков А.А. Рентгенография металлов. – М.: Атомиздат, 1977. – 480 с.

Funding. The study had no sponsorship.
Conflict of interest. The author declares no conflict of interest.
Author's contribution is 100 %.